A FLUIDIC CONTROL SYSTEM FOR A JET-FLAP AIRFOIL

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THESIS

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FOR A
JET-FLAP AIRFOIL

by

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ABSTRACT

A fluidic control system was designed, built, and tested for a jet-flap airfoil. The system was required to alleviate low frequency pitching moments caused by gusts in the airstream. An optimal, maximum effort control strategy was used.

The control system used digital fluidic devices exclusively. Details of the control system design procedure are presented. The construction of the jet-flap airfoil and a companion gust generator are also discussed.

Results of wind tunnel testing are tabulated and critiqued. The control system was effective in alleviating gusts of frequency less than two Hertz. System improvements are required for operation at higher frequencies.

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SYMBOLS

a, b - magnitudes of control moments

c - chord length

d_{AC} - distance from axis of rotation to aerodynamic center

g - distance from axis of rotation to center of gravity

j - distance from axis of rotation to jet-flap

$\dot{m}_j$ - mass flow rate of jet

t - time

t_f - final time of interval

u - total control force

v_j - velocity of jet

x - state variable

x, y, z - cartesian coordinates

C_μ - jet momentum coefficient

D - drag force

J_o - polar moment of inertia about axis of rotation

L - lift force

ΔL - lift increment

M_{AC} - aerodynamic moment

M_Z - moment about axis of rotation

P_c - control pressure

P_s - supply pressure

T - reaction force due to jet thrust

U_∞ - free stream velocity

W - weight of wing

α - attitude angle

α_o - reference or steady state attitude angle

δ - jet-flap deflection angle

ρ_∞ - free stream density

• - differentiation with respect to time

ABBREVIATIONS

dB - decibels

D.C. - direct current

Hz - Hertz

log - logarithm

NACA - National Advisory Committee for Aeronautics

Psig - pounds per square inch, gauge

scfm - standard cubic feet per minute

V/STOL - vertical or short take-off and landing

ACKNOWLEDGEMENT

The author wishes to express his appreciation for the efforts of Professor Max F. Platzer of the Department of Aeronautics of the Naval Postgraduate School. The concept of a fluidically controlled jet-flap airfoil is due solely to Professor Platzer. Throughout this project Professor Platzer acted as co-advisor. His assistance was particularly helpful in the design of the airfoil itself.

The overall guidance and encouragement of my advisor, Professor Thomas M. Houlihan is also gratefully acknowledged.

I. INTRODUCTION

The overall objective of this project was to design, build, and test a fluidically controlled gust alleviator system for a jet-flap airfoil. In a jet-flap airfoil a sheet of high momentum air is deflected at an angle from the trailing edge of the airfoil. This sheet of air can sustain a pressure difference across it which deflects the approaching airstream resulting in an increase (or decrease for upward deflection) in lift and a rearward shift in the center of pressure and aerodynamic center. Two effects contribute to the increase in lift. The reaction force due to the jet momentum has a component in the lift direction. Also, the circulation increases due to downward deflection of the flap which results in increased lift (the converse is true for upward deflection). A thorough discussion of jet-flap theory is contained in Ref. 1.

Since air is the working fluid of the jet-flap, fluidic control devices, powered by air, were a logical choice for the control system. Fluidic devices can perform many logic and control functions and are readily interfaced with electric, hydraulic or pneumatic systems. Given a supply of clean dry air fluidic devices are highly reliable. They are insensitive to environmental factors such as vibration, electromagnetic radiation, and temperature.

The jet-flap is capable of performing any of the functions of the more familiar mechanical flap. Phillips and Kraft [2] showed that flaps can satisfactorily alleviate vertical accelerations caused by a gust field provided that the flaps are properly designed to avoid severe pitching moments. The control system which was designed for this project uses the

jet-flap to alleviate pitching motion in a single-degree-of-freedom airfoil model.

II. BACKGROUND

The applicability of fluidic devices to control systems was first proposed in 1959 when the Diamond Ordnance Fuze Laboratories (now Harry Diamond Laboratories) introduced fluidics technology. The first symposia on fluidics were held by the Diamond Ordnance Fuze Laboratories and the American Society of Mechanical Engineers in October and November 1962 respectively. Thus fluidics is a relatively new technology. The synthesis and analysis of fluidic control systems are not, at this time, formalized procedures.

Analogies between fluidic and electric systems are used throughout the literature both for illustration of principles and for analysis. Terms such as fluid capacitance, inductance and resistance occur frequently in systems literature. These terms must be carefully considered because there are no universally accepted standard definitions. Equivalent circuits and transfer functions have been derived for many fluidic components. These modeling techniques are quite complex and require a solid grasp of electron tube and solid state device theory from which the techniques are derived. Belsterling [3] summarizes the available techniques as:

a) Non-Linear and Linear Mathematical
b) Graphical
c) Linear modeling

A combination of the graphical and non-linear mathematical methods plus breadboard testing were used in the development of the jet-flap control system.

Fluidic devices can be classified into the following general groups:

a) proportional (analog) components

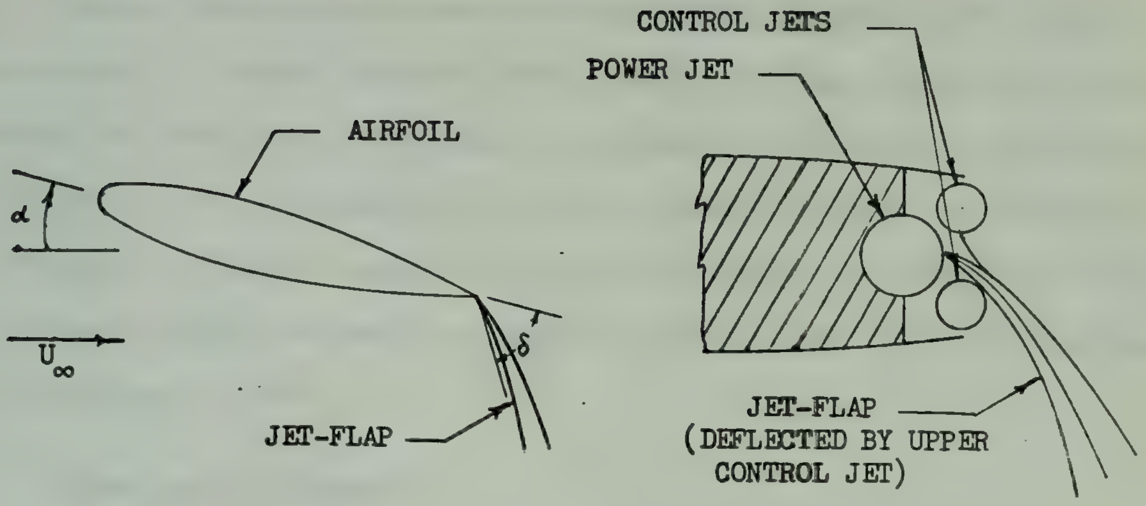
b) digital components

c) sensors

d) interfaces (fluidic-pneumatic, fluidic-electronic etc.)

e) special components

These components can be combined to form digital, analog or hybrid systems. The jet-flap design used in this project was essentially a digital device in that the jet deflection was either zero or plus or minus a fixed angle. The jet arrangement is shown in Figure 1. Three tubes span the trailing edge of the wing. The center tube, called the power tube, blows a continuous stream of air. When air blows from the upper control jet the combined streams form the jet-flap deflected downward at an angle δ. A similar upward deflection occurs when the lower jet is on. When the control pressure is sufficiently high the combined jet attaches to the opposite jet tube due to the Coanda effect. Further increases in control pressure do not increase the jet deflection significantly. This saturation effect suggested using the jet-flap as a "maximum effort" or "bang-bang" type of control. And so it was decided to fix the power and control jet pressures thus fixing the jet deflection angles. This in turn suggested the use of digital rather than proportional fluidic devices.



JET-FLAP AIRFOIL

TRAILING EDGE DETAIL

FIGURE 1

JET-FLAP GEOMETRY

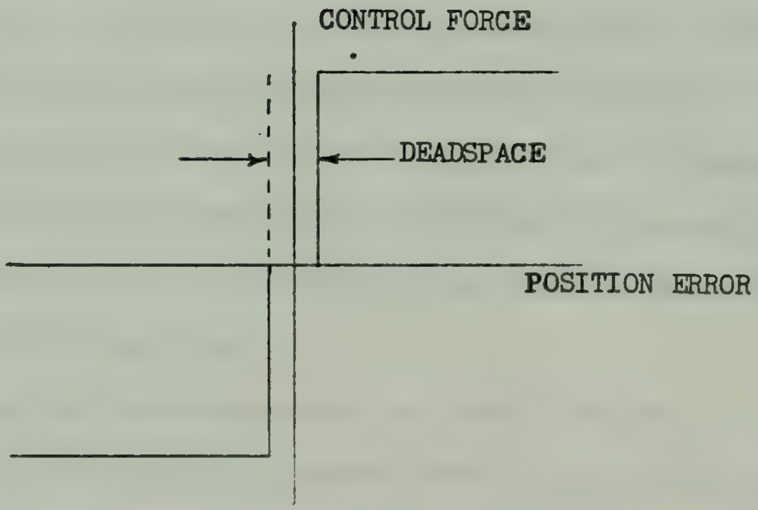


FIGURE 2

RELAY SERVO CHARACTERISTIC

III. CONTROL SYSTEM THEORY

The gust alleviation scheme chosen consisted of pitching the airfoil to maintain a constant attitude during passage through a gust field. This method was dictated by the physical arrangement of the airfoil built for the project. Rose and Smith [4] reported limited success in the design and test of a fluidic control system which maintains constant lift force in a gust field. The merits of these (and other) gust alleviation schemes are discussed in Ref. 2.

A. SYSTEM DESIGN PARAMETERS

The system output was defined as the airfoil absolute attitude angle (α). Since this was to be maintained at a prescribed value the control system is defined as a regulator. The control mechanism is the jet-flap and the load is the airfoil itself. In order to design the control system a control strategy had to be developed. As previously stated, the maximum-effort control was suggested by the existing design of the jet-flap. A maximum-effort controller, sensing position error only, has a characteristic as shown in Figure 2. The dead space may be designed into the controller or may be the result of insensitivity of the position sensor to small errors. The control force is the pitching moment caused by the deflection of the jet-flap.

A control system with a characteristic as shown in Figure 2 (called a relay servo) has the advantages of minimum rise time, simplicity, and economy. A simple relay servo however, is normally unstable or has a limit cycle of unacceptable amplitude. Some means of compensation is needed to reduce the amplitude of the limit cycle and stabilize the system.

The frequency range of the gust disturbances to be controlled was chosen as zero to four Hz. Phillips and Kraft [2] reported that low frequency, high amplitude, vertical accelerations were a major cause of passenger discomfort. They reported some data to verify this contention.

IV. CONTROL SYSTEM DESIGN

A. CONTROLLABILITY

The first question to be answered in the overall design was: "Is the wing controllable using the selected control strategy". To answer this question the wing dynamics had to be modeled in a manner which was representative of the actual wing and was also mathematically tractable. The wing was mounted on oversize ball bearings to reduce static and rolling friction. Furthermore, it was found that viscous damping was very low. Since damping would have a stabilizing effect on a relay control system, the assumption of no damping corresponds to the worst possible case. With the assumption of no friction or damping the equation of motion for the wing is,

$$\Sigma M_z = J_o \ddot{\alpha}$$

where the coordinate origin is the axis of rotation.

A free body diagram of the wing is shown in Figure 3. Under steady-state conditions the moment due to the lift force is balanced by that of the weight. The aerodynamic moment is zero since the airfoil is symmetric and the jet reaction has no moment since the deflection δ is zero. In a dynamic situation the summation of moments is an extremely complex expression.

$$\Sigma M_z = J_o \ddot{\alpha} = L\, d_{AC} \cos\alpha + D\, d_{AC} \sin\alpha - Wg \cos\alpha + M_{AC} - T_j \sin\delta$$

In this expression the lift and drag forces are functions of α and δ. Furthermore, d_{ac} and M_{ac} are functions of δ. None of these functions can be expressed in closed form.

From a control theory standpoint, the system input, output and control forces and excitation force must be defined. The output has previously

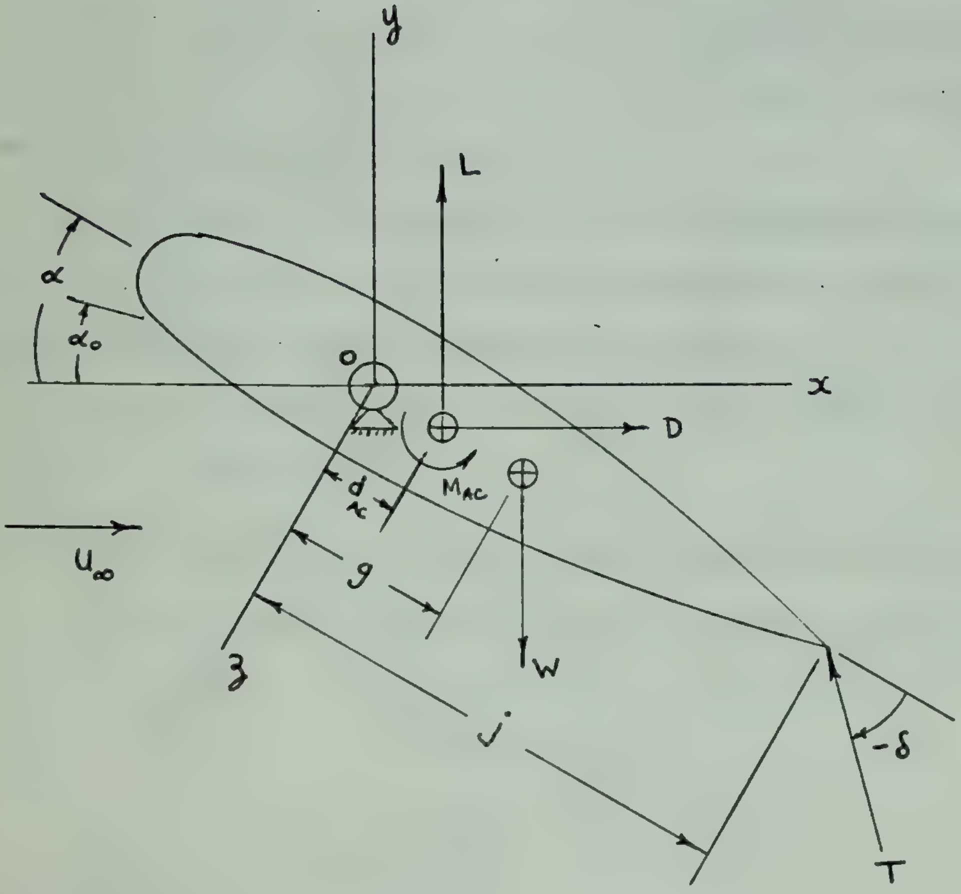


FIGURE 3

FREE BODY DIAGRAM
OF WING

been defined as α, the attitude angle with respect to a fixed coordinate system. The control forces (moments) are the aerodynamic moment M_{ac}, the moment of the jet force reaction Tj sin δ and the moment of the lift increment due to the flap deflection. The excitation is the moment due to the increments in lift and drag which are caused by the gust field. The input is the desired attitude, α_o.

The lift increment may be expressed as:

$$\Delta L = \frac{\partial L}{\partial \alpha}\alpha + \frac{\partial L}{\partial \delta}\delta = \Delta L_i + \Delta L_c$$

Where $\frac{\partial L}{\partial \alpha}\alpha \equiv \Delta L_i$, is the change in lift force due to the gust field and $\frac{\partial L}{\partial \delta} \equiv \Delta L_c$, is the lift increment due to the deflection of the jet-flap.

The steady state lift moment on the wing is identically equal to the moment of the weight. In order to gain some physical insight into the control problem the following assumptions are made:

a) $L\, d_{ac} \cos\alpha = (L_o + \Delta L_i + \Delta L_c)\, d_{ac} \cos\alpha$ where L_o is the steady state lift at α_o

b) $L_o\, d_{ac} \cos\alpha = Wg \cos\alpha$, under dynamic conditions.

c) $D\, d_{ac} \sin\alpha$ is small in comparison with the other moments since,

$$D \simeq 0.1\, L$$
$$\sin\alpha < \cos\alpha$$

d) T is a constant force

With these assumptions the equation reduces to:

$$\Sigma M_z = J_o \ddot{\alpha} = \Delta L_i\, d_{AC} \cos\alpha + \Delta L_c\, d_{AC} \cos\alpha + M_{AC} - Tj \sin\delta$$

The last three terms in this expression are the control forces. They all act in the same direction depending on the jet deflection δ. If δ is positive M_{ac} is negative and ΔL_c is negative because $\frac{\partial L}{\partial \delta}$ is negative. Since δ is fixed in absolute value by the geometry of the jet-flap, ΔL_c,

M_{ac} and $\sin\delta$ are discreet values. Furthermore, they are all equal to zero when the jet-flap is not deflected. The total control force,

$$u = \Delta L_c \, d_{AC} \cos\alpha + M_{AC} - T_j \sin\delta$$

very nearly approximates a relay control. The moment arm of the lift increment, $d_{ac} \cos\alpha$, varies continuously with α, the dependent variable. If the wing pitches upward, this moment arm decreases and vice versa. Since the wing is symmetric α_o must be positive to produce lift. This means that the term $d_{ac} \cos\alpha$ is not symmetric about the steady state or zero error position. The moment arm is greater if the wing pitches down from this position than it is if it pitches upward an equal amount.

Assuming that the total control force is asymmetric but neglecting the cosine variation in the term $d_{AC} \cos\alpha$, the characteristic of the total control force is as shown in Figure 4.

To demonstrate controllability only the total control forces and the system dynamics are considered. By definition the system is controllable if it is possible to transfer it between specified states in some interval $o < t < t_f$ with the control force u. The states for this system are:

$$x_1 = \alpha - \alpha_o$$

$$x_2 = \dot{\alpha}$$

Without excitation the equation of motion is,

$$J_o \ddot{\alpha} = u$$

and the state equations are:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{J_o} u$$

where,

$$u = +a \quad , \quad x_1 > 0$$

$$u = -b \quad , \quad x_1 < 0$$

$$u = 0 \quad , \quad x_1 = 0 .$$

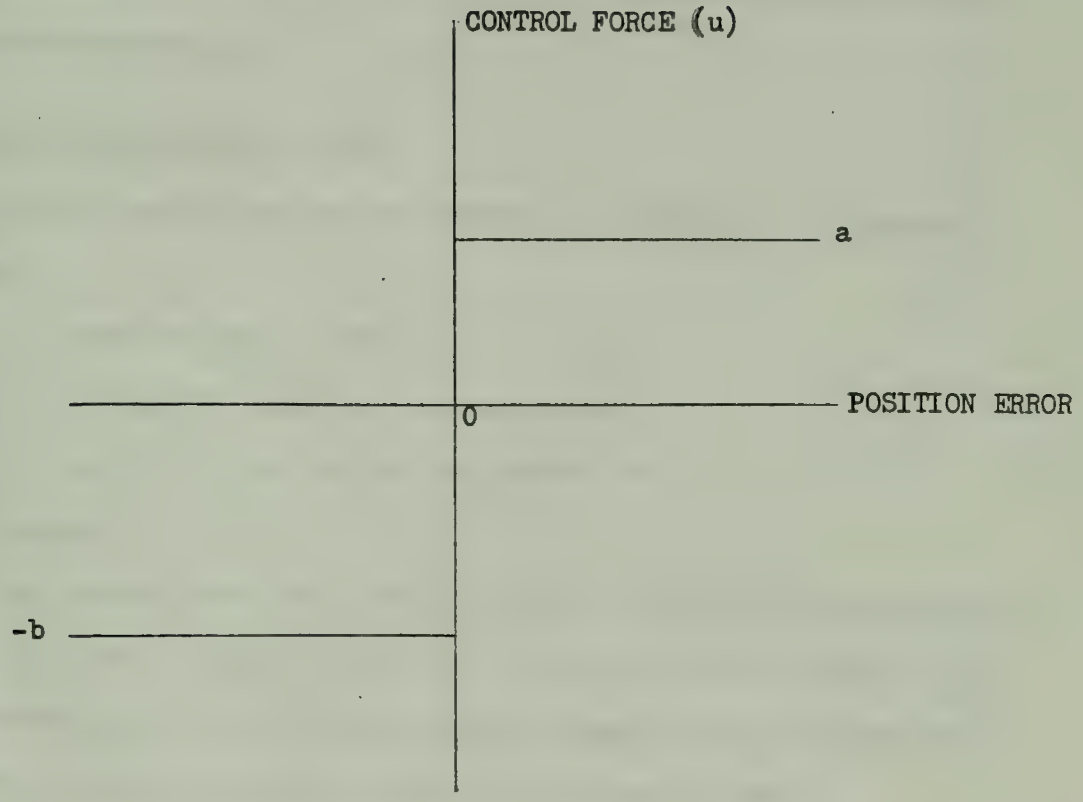


FIGURE 4

TOTAL CONTROL FORCE
CHARACTERISTIC

Elgerd [5] proves the controllability of precisely this system of equations using discreet values for the control force and one switching during the control interval. He further shows that there are an infinite number of possible control strategies of this type which will bring the system to a specified state in as short a time interval as is desired provided the control forces are unbounded. Practically, there are bounds on the control forces and on the attainable states. But, if the time interval is sufficiently long and the control forces strong enough the system can be controlled.

B. FLUIDIC CONTROL SYSTEM DESIGN

The fluidic control system was required to perform the following functions:

1) sense the wing position
2) turn on the jet-flap (control force)
3) switch the jet-flap at the proper time

1. Sensing

The simplest available position sensor was the interruptible-jet sensor. This device consists of a jet of air which blows across a gap into a receiving port. The output is the pressure from the receiving port. When an object interrupts the jet the output is off.

The primary concern for all components in the system was that of time delay. Rapid switching of the control jets would insure good response of the wing. Since no data was available from the manufacturer, the jet sensors were tested upon receipt. The time delay between the removal of an object from the sensor and the realization of full pressure at the output was found to be 15 milliseconds. Although undesirable this delay was deemed tolerable. Additionally, every effort was made to reduce

line lengths between these sensors and the following components in the system.

2. Interfacing

To turn on the control jets an interface device was required which could be activated by the low output pressures of a fluidic device and could provide sufficient flow to the jets. A pair of fluidic-pneumatic interface valves of an early design were available. The flow capacity of these valves was found to be adequate. A test stand, shown schematically in Figure 5, was built to determine the frequency response and rise time of these valves. This same test setup was used to measure the time delay in the interruptible-jet sensors.

In this test setup a blade was rotated by a D.C. motor through a reduction gear. The speed range could be varied between 0.1 and 20 revolutions per second. The passage of the blade produced a pulse in the proximity sensor; the period between pulses was measured on a digital electronic counter-timer. The pressure pulses from the interruptible-jet sensor and from the valve were displayed simultaneously on a two-channel chart recorder. The fluidic amplifier consisted of a NOT element and two digital amplifier stages. The NOT element sent a pressure pulse to the valve through the amplifiers when the blade passed through the jet sensor. This pulse turned on the interface valve. From the output of the chart recorder the time lag between the cutoff of the jet sensor and the opening of the valve could be measured. Also the magnitude of the pulses and their shape were determined. The frequency response of the valves was plotted from the charts. The ratio of output to input pressure, in dB, was plotted against the log of frequency. The original valves had a frequency response of less than 0.5 Hz. which was unsatisfactory. Corning Fluidamp valves were ordered and similarly tested. A

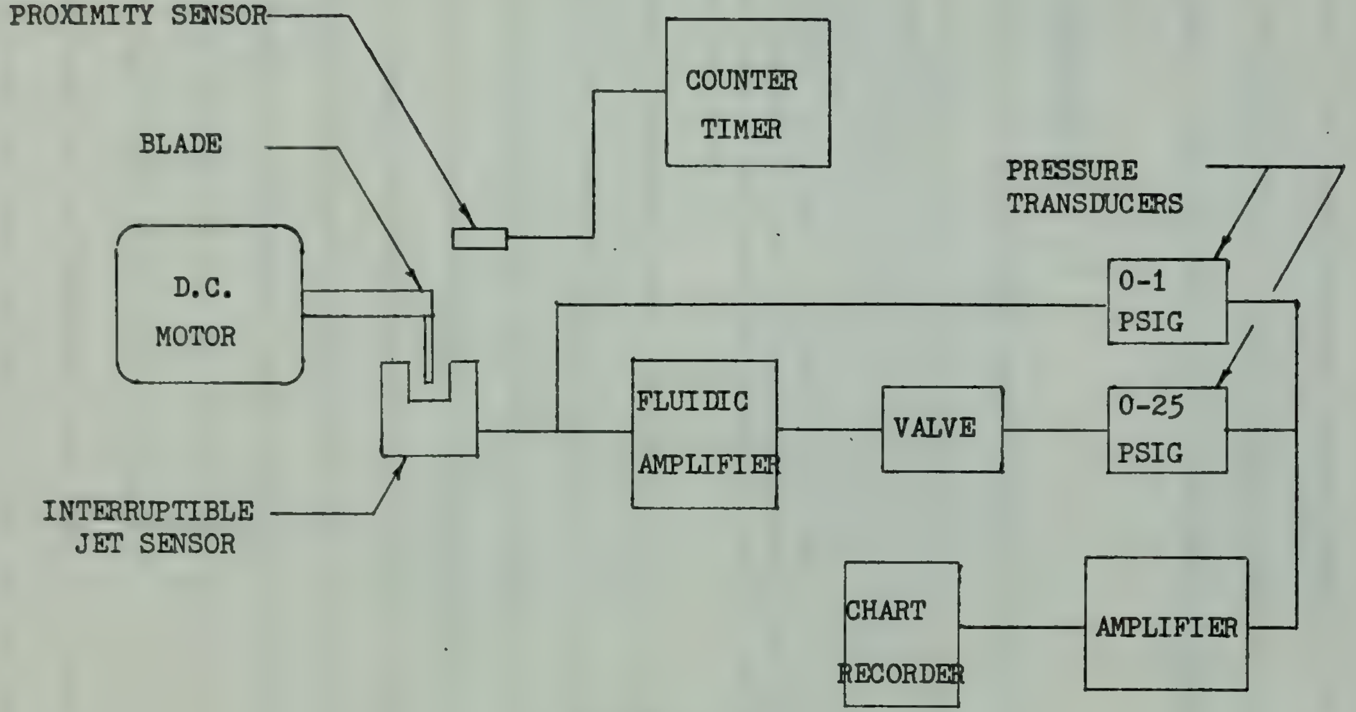


FIGURE 5

VALVE FREQUENCY RESPONSE TEST SCHEMATIC

frequency response of better than 7.0 Hz was measured; the pressure ratio was -3 dB at 7.0 Hz. The rise time of these valves was approximately 20 milliseconds as was the drop time. It was also found that the valves operated satisfactorily at input pressures corresponding to the output pressure of a fluidic logic device. Thus digital amplifiers were not needed in the system. Based on these results the Corning valves were selected for use.

3. Fluidic Logic Circuit

In describing an optimum relay servo Thaler and Pastel [6] state:

> "Full motor torque must be used to accelerate the output, but in order to prevent overshoot, full motor torque must also be used to decelerate the output; thus a derivative signal of some type must be used to reverse the relay before the error reaches zero. For a second-order system, if this point of reversal is properly selected, the system is decelerated so that zero error and zero error rate are reached simultaneously in which case the relay remains in the neutral position and the system is stationary at zero error."

This statement summarizes what the fluidic logic was designed to do. It had to apply full pressure to the control jet to accelerate the wing toward the neutral position and switch at the proper time to decelerate the wing to rest. In a sinusoidally varying gust field the system had to repeat this process with each reversal of the gust direction. The turn-on and switching points were determined by the output of two sets of interruptible-jet sensors activated by vanes attached to the wing. These vanes and sensors are shown in Figure 6, the overall system schematic. The fluidic symbols along with their logic tables are given in Figure 7. The first sensor J1 turns on when the wing moves off the neutral position (which was set by aligning the vane to the wing) and the vane uncovers the jet. The sensor output is led to the control port of an INHIBITED OR component, IOR 1, which turns on the interface valve. This component was chosen to control the interface valve because it has an override control

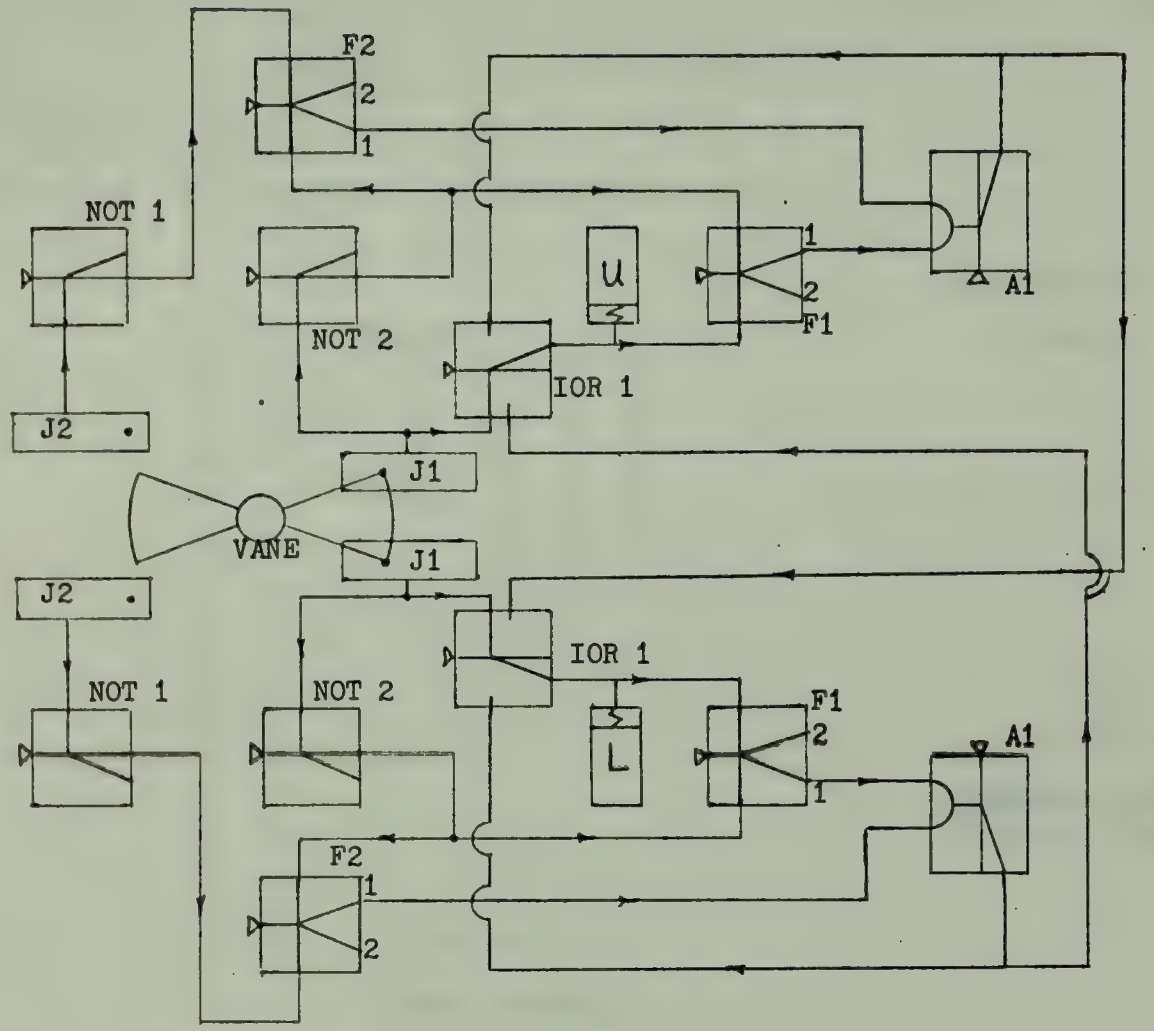
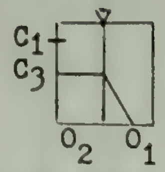


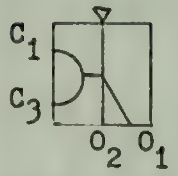
FIGURE 6

CONTROL SYSTEM SCHEMATIC



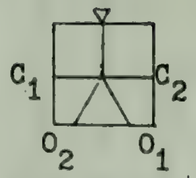
OR/NOR GATE

C_1	C_3	O_1	O_2
O	O	O	X
O	X	X	O
X	O	X	O
O	O	O	X



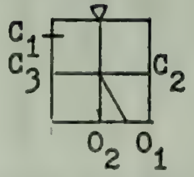
AND/NAND GATE

C_1	C_3	O_1	O_2
O	O	O	X
O	X	O	X
X	O	O	X
X	X	X	O
O	O	O	X



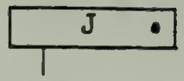
FLIP-FLOP

C_1	C_2	O_1	O_2
O	O	INVALID	
X	O	X	O
O	O	X	O
O	X	O	X
O	O	O	X
X	X	INVALID	



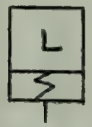
INHIBITED OR GATE

C_1	C_2	C_3	O_1	O_2
O	O	O	O	X
O	O	X	X	O
O	X	O	O	X
O	X	X	O	X
X	O	O	X	O
X	O	X	X	O
X	X	O	O	X
X	X	X	O	X
O	O	O	O	X



INTERRUPTIBLE JET

SENSOR



INTERFACE VALVE
(L-LOWER, U-UPPER)

FIGURE 7

FLUIDIC SYMBOLS

port which, when activated, will switch the output and shut off the valve. IOR 1 also sets the 1 output of flip-flop F1. The flip-flops are the memory components of the system which activate the switching of the interface valves. As the vane continues to rotate it interrupts the second jet sensor. The output of this sensor turns off. This loss of signal activates the logical NOT component, NOT 1. The output of NOT 1 sets output 1 of another flip-flop, F2. This is the instant when switching occurs. Both F1 and F2 are in state 1; since these states are connected to the control ports of the AND component, A1, it turns on. The signal from A1 turns off the interface valve through the override port of its INHIBITED OR and turns on the interface valve on the opposite side by activating the INHIBITED OR of that valve. Assuming now that the wing has returned to the neutral position, the vane cuts off sensor J1. This turns on NOT 2 which resets the flip-flops to state 2. This turns AND, A1, off and hence the opposite interface valve shuts off.

The design of the system, then, consisted of choosing the logic components to perform a predetermined sequence of events. The logic components were all manufactured by the Corning Glass Works and were designed for ease of matching. Fan out, the number of components driven by an output, was the only matching parameter requiring consideration in the logic circuit.

The jet sensors, purchased from another manufacturer, (Bowles Fluidics) had to be matched to the inputs of the logic components. This required breadboard testing of the circuit. The procedure was to set the supply pressure to the sensors, and to vary the supply pressure to the associated OR/NOR components until the sensors could satisfactorily switch them. Then using the performance curves in Ref. 7 the supply pressures were sequentially set throughout the logic circuit. A panel mounted

manifold of pressure regulators was an indispensible tool used for this sequence. Sufficient regulators were available to independently vary each supply pressure. The final system pressure balance, which gave the most reliable performance is tabulated below.

TABLE 1

SYSTEM PRESSURE BALANCE (psig)

COMPONENT	FANOUT	SUPPLY PRESS. (P_S)	OUTPUT PRESS.	CONTROL PRESS. (P_C)	P_C/P_S
J1	2	10.0	1.0	-	-
J2	1	10.0	1.0	-	-
IOR 1	1	5.0	1.0	1.0	0.2
NOT 1	1	5.0	1.0	1.0	0.2
NOT 2	2	5.0	0.8	1.0	0.2
F1	1	7.5	1.5	0.8	0.106
F2	1	7.5	1.5	0.8	0.106
A1	2½	7.5	1.2	1.5	0.2

The critical parameter is the ratio of control to supply pressure. For positive switching this ratio must be greater than 0.1. Thus the flip-flops F1 and F2 were the most sensitive to supply pressure changes. The fanout of AND, A1, is 2½ because of the high input impedance of the override control of IOR 1. For design purposes this control port is considered as a fanout of 1½.

4. System Operation

The system operation is summarized in the following sequence.

When the wing pitches upward sensor J1 turns on the upper control jet through IOR 1 and sets the 1 output of F1. The jet-flap is deflected downward tending to pitch the wing downward. As the wing nears its maximum upward deflection sensor J2 sets the output of F2 to the 1 port through NOT 1. As both flip-flops are in the 1 state A1 turns on. This shuts off the upper control jet, through IOR 1, and turns on the lower control jet through IOR 1 of that side of the control system. This deflects the jet-

flap upward to decelerate the wing to the neutral position. When the wing reaches the neutral position sensor J1 turns off so that NOT 2 resets the flip-flops, F1 and F2, and the lower jet is turned off by A1. A similar sequence occurs when the wing pitches downward.

V. WING DESIGN

As previously noted, a jet-flap airfoil was available but was being used concurrently. Also, for scheduling reasons, it was necessary to use the Mechanical Engineering Department's wind tunnel. The existing airfoil would have required extensive modification to mount it in this tunnel. It was decided to build a similar airfoil with a different mounting arrangement.

A. DESIGN CONSTRAINTS

The primary constraint which affected the design was the availability of sufficient air to operate the jet-flap. Jet flap effectiveness increases directly with the jet momentum coefficient C_μ which is the ratio of the jet reaction to the free stream momentum [8]. The momentum coefficient per unit span is defined as:

$$C_\mu = \frac{\dot{m}_j v_j}{\frac{1}{2}\rho_\infty U_\infty^2 c}$$

To obtain a high momentum coefficient the mass flow rate must be large. Because of limited air compressor capacity the span of the wing had to be approximately one foot.

The second major constraint was the wind tunnel arrangement. The test section is 20 inches wide by 30 inches high. Access to the test section is through Plexiglas doors which are hinged at the top. The mounting platforms for test shapes are outside the wind tunnel on either side. The wing was built on an axle which extended through the doors of the tunnel. In order to place the wing in the tunnel one axle was pushed through until the wing was against the far wall, the door was closed and

the wing was pushed back to extend the other axle out the door to the mounting platform. A 12-inch wingspan with an 8-inch axle on each side would just fit in the tunnel.

Fitting the power and control jets into the tail of the wing meant that either a blunt wing or long wing be made. It was determined that the jets could be fitted into a NACA 0012 airfoil with a nominal 15-inch chord cut off at an 80 percent (12-inch) chord length. The jets were installed at the 80 percent chord giving the wing a thickness ratio of 0.147.

B. DESCRIPTION OF THE WING

The wing was a NACA 0012 airfoil with the jet-flap installed at the 80 percent chord. The cross section plan for this wing was taken directly from Ref. 9. The leading edge, back to the 13.5 percent chord was milled from aluminum bar and hand shaped to the final contour. The inside of this bar was milled out to reduce its weight. Four ribs were cut and hand finished to form the remainder of the wing contour. The ribs were dovetailed into the leading edge and spaced by two frames each, top and bottom. The axle, 3/4-inch aluminum pipe, passed through the ribs at the 18.3 percent chord, forward of the aerodynamic center. This pipe was split inside the wing to pass the air tubing to the jets. The power jet, located at the 80 percent chord, was rigidly fastened to the ribs. The control jets were fitted in slots in the outer ribs so that the spacing between them could be varied (see Figure 8). All of the jets had 44, .030 inch, holes at 1/4-inch intervals drilled for air flow. The power jet was fed by 1/4-inch I.D. plastic tubing passing through one side of the axle. The control jets were supplied by .180 I.D. polyethylene tubing passing through the opposite side of the axle. The ribs were covered with .020 inch aluminum sheet held in place by contact cement. Most of the

construction was held together by epoxy cement with only the fittings to the jet tubes being brazed. The aluminum sheet was faired into the leading edge with DEVCON. The wing was given two coats of paint and one of varnish to give a smooth surface. The axles were machined to 1.000 inch diameter to fit the mounting bearings at the wind tunnel.

The mechanical properties of the wing are listed in Table 2.

TABLE 2

MECHANICAL PROPERTIES OF WING

Weight	5.42 lbs.
Location of center of gravity	1.26 inches aft of axle (.275 chord)
Moment of Inertia	about C.G. = .0051 slug-in about axle = .2734 slug-in
Length	12 in.
Width	12 in.

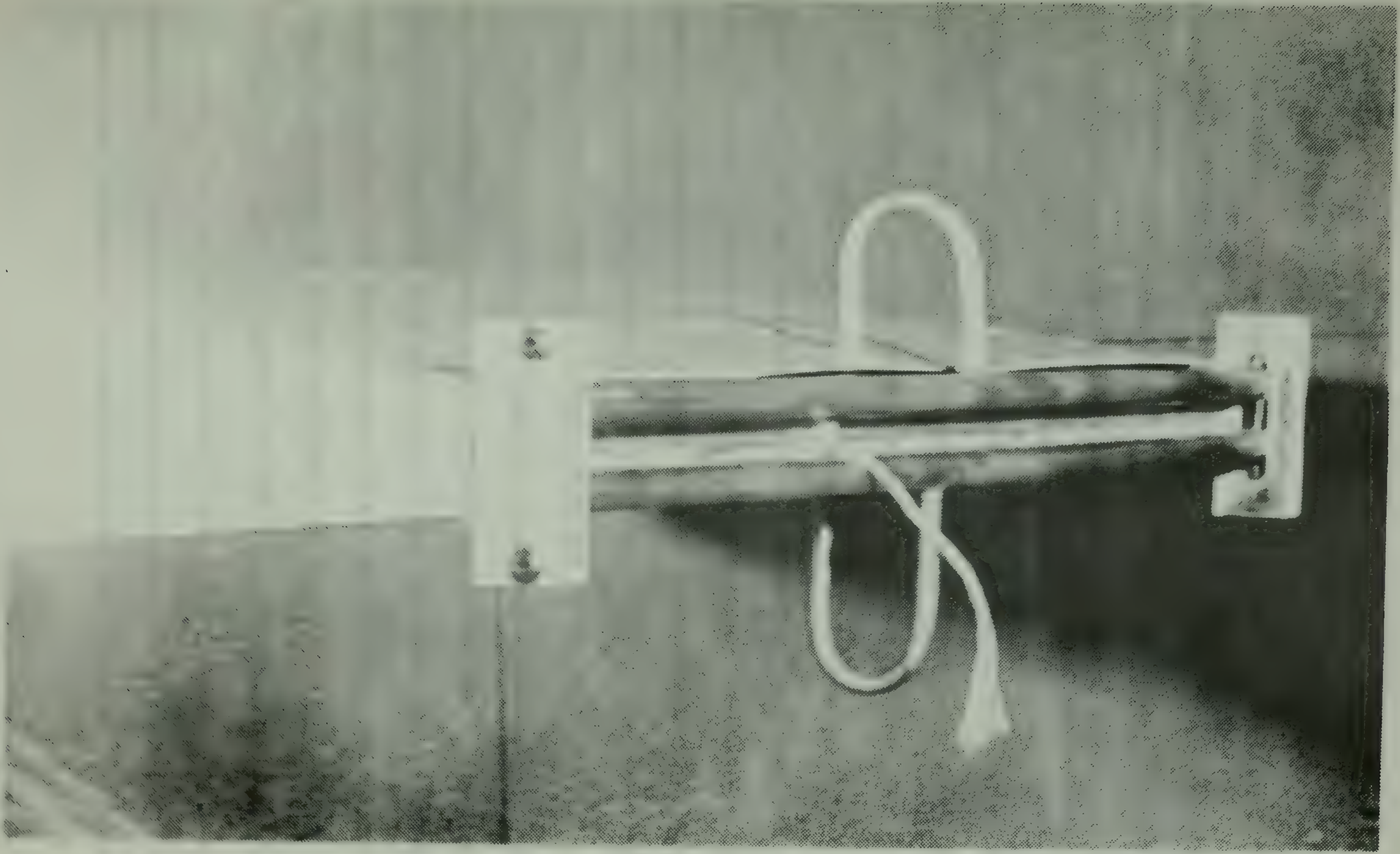


FIGURE 8

JET FLAP CONFIGURATION

VI. THE GUST GENERATOR

The purpose of the gust generator was to create a sinusoidally varying vertical component of velocity in the free stream. The existing gust generator used a stationary airfoil with an oscillating jet-flap to produce the gust field. Due to the critical supply of air available an attempt was made to build a mechanical gust generator. The disturbances were to be generated by oscillating plates driven through a scotch-yoke mechanism by a D.C. motor. This attempt was unsuccessful primarily because the plates had to be mounted too far forward of the test section.

The oscillating jet-flap was modified to fit the wind tunnel. This device was also unsuccessful in creating enough of a disturbance to excite the wing. Previously, this style of generator had been successful used in conjunction with a lighter wing in a lower speed wind tunnel with a much larger test section area. This wing had also been restrained by a spring which prevented it from moving out of the gust field.

No further attempts were made to generate a controlled gust field due to an unexpected advance in the project completion date. However, it was possible to make the wing oscillate rather violently by setting the wind tunnel speed so that the frequency of vortex shedding coincided with the natural frequency of pitch oscillation of the wing. By means of a counterweight the center of gravity of the wing could be moved relative to the axle. This varied the natural frequency of the wing and hence the frequency at which the oscillations occurred. The vortex shedding phenomena made it possible to evaluate the effectiveness of the control system.

VII. TEST EQUIPMENT AND PROCEDURE

A. MOUNTING ARRANGEMENT

As much as possible, the mounting hardware from a previous wind tunnel project was used. Platforms stood on either side of the test section and were fixed to each other by braces running under the test section. Bearing pedestals were made for oversize ball bearings in which the wing axle rotated (see Figure 9). These bearings were cleaned of all grease and sprayed with a light lubricant to minimize friction. The axle of the wing fitted through holes in the wind tunnel doors into the bearings. On one side of the tunnel the counterweight was clamped to the axle between the door and the bearing pedestal. The counterweight was sized so that the center of gravity of weight and wing could be moved as far forward as the axis of rotation. Between the other door and bearing an aluminum pulley wheel was fitted to the axle. This pulley had two grooves machined in it for o-rings. The o-rings were used to drive a potentiometer and a tachometer generator which were similarly fitted with pulleys. The position vanes were mounted on the axle, outboard of the bearing. The angle between the centerline of the vanes and the wing chord was set by rotating the vanes then fixing them with a setscrew. The control system, mounted on an aluminum plate was clamped to the platform so that the vanes were aligned with the interruptible jet sensors. The fully assembled system is shown in Figure 10.

B. AIR SUPPLY

Two compressors were used, the house air compressor supplied the power jet directly and the control jets intermittantly through the interface

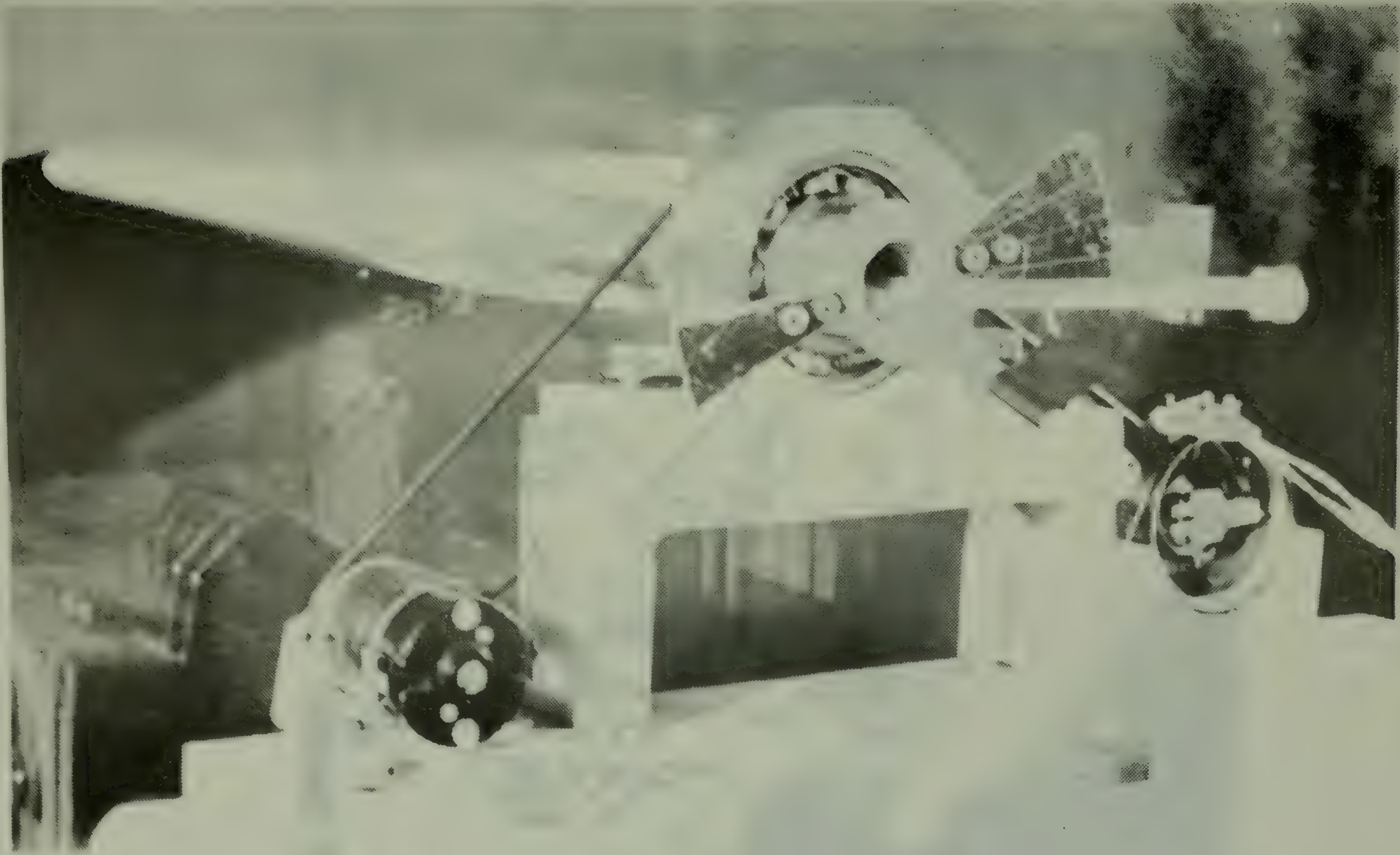


FIGURE 9

MOUNTING ARRANGEMENT

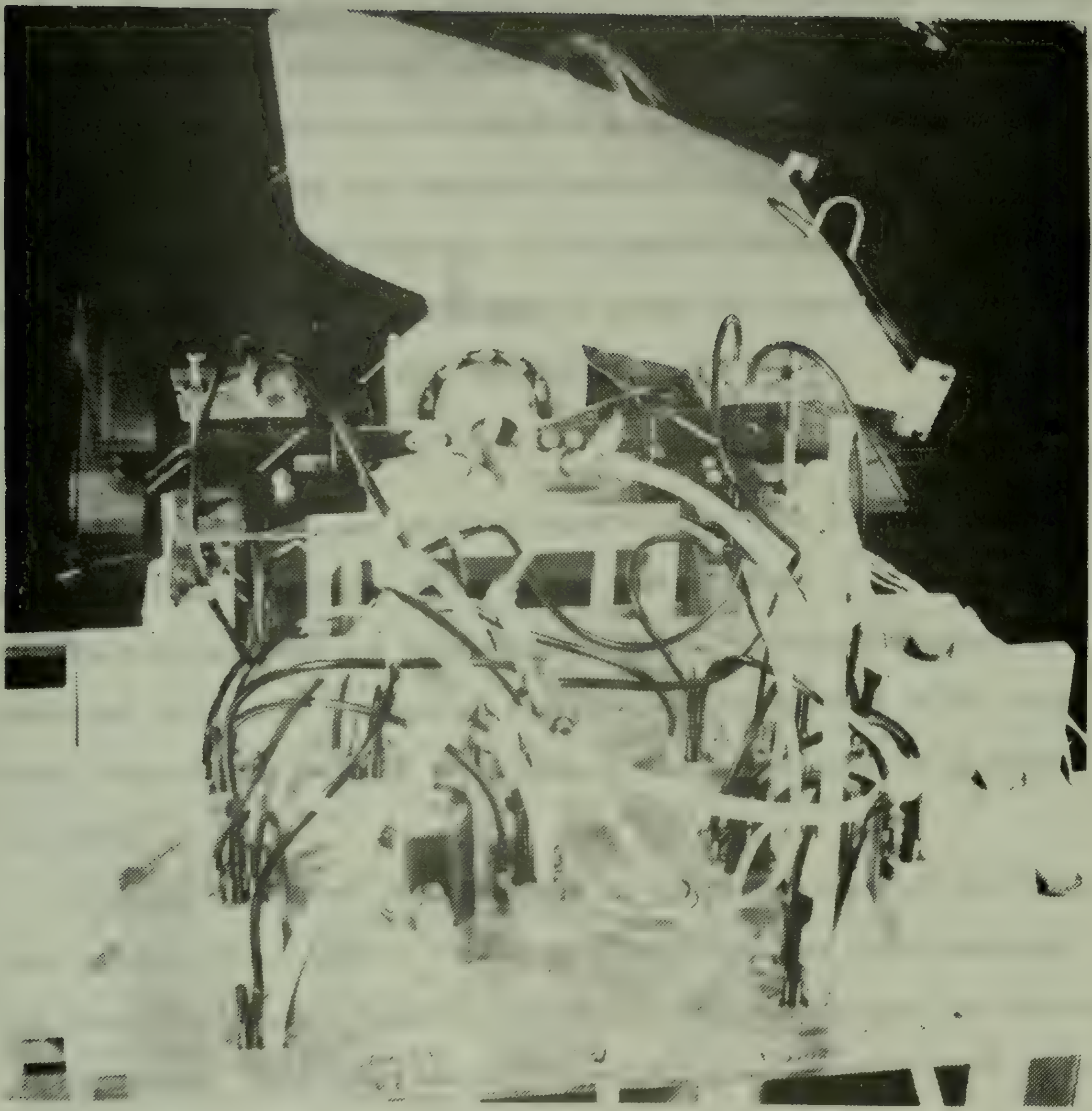


FIGURE 10

ASSEMBLY OF WING AND CONTROL SYSTEM

valves. A regulator maintained the supply to the jets at 55 psig but due to line losses and valve losses the control jet pressure was 22 psig with the valves wide open. A portable compressor supplied air to the fluidic sensors and control devices through a manifold of regulators. These regulators maintained the supply pressures to the sensors and logic components. The use of fluidic resistors to maintain system pressures was successfully tried but the regulator manifold allowed more flexibility for test purposes. The capacity of the portable compressor, 7 scfm, was more than sufficient to run the control system but insufficient for either the wing jets or the gust generator.

C. INSTRUMENTATION

Wind tunnel speed was measured using a pitot tube mounted upstream of the airfoil through the floor of the test section.

The potentiometer and tachometer generator, previously mentioned, were used to measure the angular displacement and velocity of the wing. Their outputs were recorded simultaneously on two channels of a chart recorder.

Pressure transducers were inserted in the output lines of the interface valves. These outputs were also displayed on the chart recorder. The chart then, gave a time history of velocity, displacement and control jet pressures. From these charts the switching sequence could be monitored by comparing the pressure and displacement traces. Phase plane plots were made from the velocity and displacement data. The shape, amplitude and frequency of all signals were conveniently displayed.

D. TEST PROCEDURE

Prior to each test run the pressure transducers and the potentiometer were calibrated. To calibrate the pressure transducers the range of the

amplifiers was set by adjusting the zero and then trimming the gain using a built-in calibration voltage. The range of amplifier output, zero to one volt D.C., corresponded to 0 to 100 psig at the transducers. The chart recorder zero and full scale deflections were adjusted to a convenient scale using the calibration signals from the transducer amplifiers. This scale was chosen as one chart line per one psig.

The chart recorder was used to calibrate the potentiometer. The wing was held in the horizontal position and the chart recorder was set to zero deflection. The wing was then held in the vertical position and the voltage to the potentiometer was adjusted to give a full scale reading on the recorder. The most convenient scale was found to be 4.0 volts per $\pi/2$ radians.

The calibration of the tachometer generator had previously been determined to be 0.06 volts per radian per second. Only the zero adjustment had to be checked on this channel of the recorder.

To make a test run the counterweight was adjusted to vary the natural frequency of the wing. Moving the weight forward of the axle lowered the frequency and moving it aft had the opposite effect. The wind tunnel was then started and its speed adjusted to produce oscillation of the wing. The manometer reading from the pitot tube was recorded when the wind tunnel speed reached steady state. The chart recorder was started and then the control system was turned on. When the control system had damped out the oscillations the recorder and control system were shut down. This procedure was repeated for several tunnel speeds with the counterweight in different positions so that the effectiveness of the controls could be observed at varying frequencies of oscillation.

VIII. RESULTS

The system consistently was able to eliminate oscillations of frequency up to two Hz. and of amplitude up to 0.2 radians. On the average these oscillations were eliminated 2.2 seconds after the control system was activated. At frequencies above two Hz., the system behaviour was erratic. Amplitude of oscillation was reduced from 21 to 88 percent at these frequencies. The results are summarized in Table 3.

At the higher frequencies the amplitude of oscillation was greater. Frequency and amplitude could not be controlled independently during the tests. The amplitude was determined by wind speed, wing dynamics and a jump resonance phenomena. The last two entries in the table are an example of this phenomena. The natural frequency of the wing is nearly equal for these runs. The wind tunnel speeds and oscillation amplitudes, however, differ significantly. The lower amplitude occurred when wind tunnel speed was decreased from above the resonant condition and vice versa.

A typical time history of position and velocity, as plotted on the chart recorder, is shown in Figure 11. The corresponding phase plane plot is given in Figure 12. The spikes on the velocity trace are due to the stretching of the rubber as the tension in the o-ring, driving the tachometer, reversed direction. Since the inertia of the potentiometer was very low, the tension in its o-ring could be kept low without any slipping. This resulted in the smoother trace of the position, which was practically sinusoidal.

The phase plane plot is not symmetric about the origin. This illustrates two problems of the system. The switching of the control jets was

TABLE 3

SUMMARY OF TEST RESULTS

Frequency (Hz)	Amplitude (radians)	Wind Speed (ft./sec.)	Settling Time (sec.)	o/o Control (note a)	Limit Cycle	Remarks
1.43	.137	41.8	2.4	100	no	-
1.52	.133	41.8	2.5	100	no	-
1.53	(note b)	49.7	2.3	100	no	-
1.55	(note b)	56.5	2.0	100	no	-
1.64	.157	56.1	2.2	100	no	-
2.08	.216	(note b)	2.1	88	yes	-
2.25	.196	66.2	21.2	32-100	no	1
2.38	.186	76.7	none	21	-	2
2.44	.174	65.9	8.5	46-90	yes	3
2.49	.230	90.1	none	32	-	4

NOTES:

a) o/o Control = per cent reduction in amplitude with control on.

b) - not recorded or not calculated due to calibration error.

REMARKS:

1. Controls reduced oscillations 32% then after 21.2 seconds the wing came to rest with the upper jet on continuously.

2. The vane and sensors were not properly aligned, switching occurred too soon during one half of the cycle.

3. System reduced oscillations by 46% then after 8.5 seconds the system went a limit cycle with the upper jet pulsing.

4. Switching was not properly timed, the oscillations stopped when the control system was turned off.

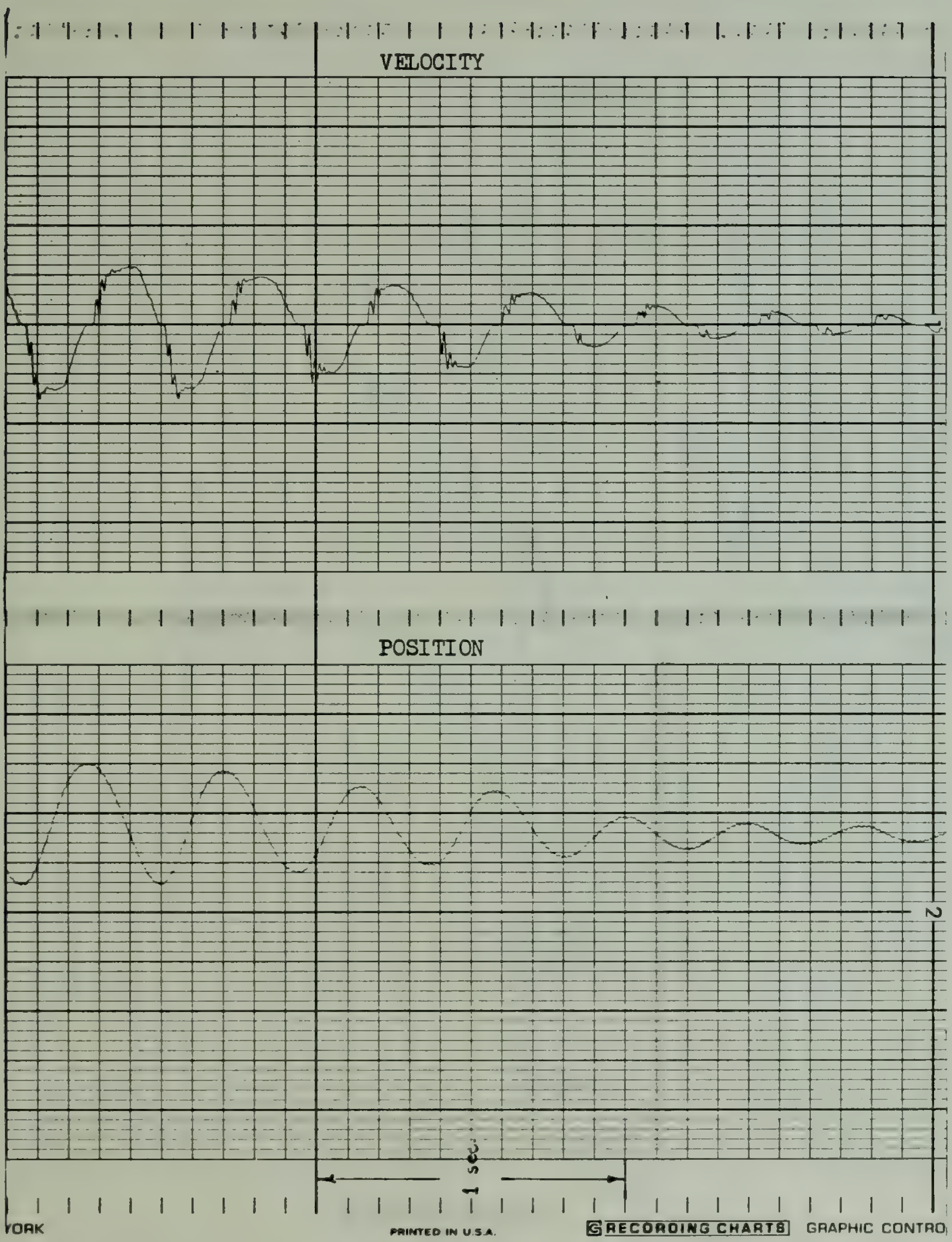


FIGURE 11

TIME HISTORY, VELOCITY AND DISPLACEMENT

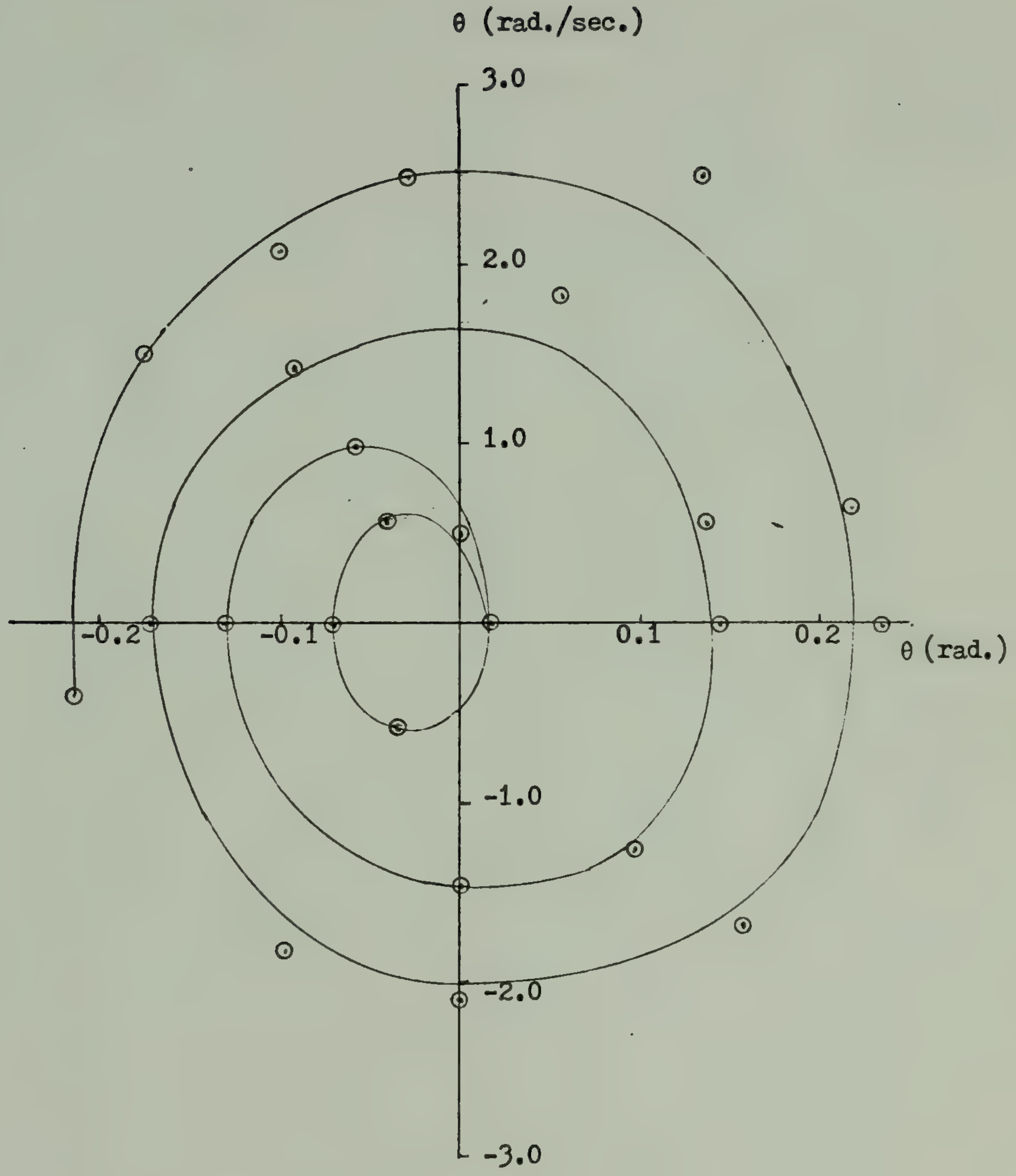


FIGURE 12

PHASE PLANE PLOT

not symmetric and the magnitudes of the upward and downward control forces were not equal. The asymmetry or improper timing of the system was the major cause of poor performance at higher oscillation amplitudes.

IX. CONCLUSION

A. CRITIQUE

1. The Control System

The control forces were shown to be capable of damping out oscillations of significant amplitude. The selected control strategy proved to be adequate, justifying the assumed discreet magnitudes of the control forces.

The major faults of the system lie in the mechanical design of what may be called the operator's controls. The setting of the vane position by hand using a setscrew was crude. This caused the system to frequently go into a limit cycle due to the error between the steady-state angle of attack and the vane setting. The other manual input, which could be called the amplitude control, sets the gap between the jet sensors J2. This gap determined the switching point of the system. With the current arrangement, the operator would increase this setting for high amplitude gusts or decrease it for mild gusts. This was accomplished by adjusting four nuts on a threaded post which supported the sensors. Furthermore, both of the above settings were estimated by eye. It was a trial and error procedure to cause the system to switch at the proper amplitudes of upward and downward deflection.

2. Wing Design

The wing span was limited by the availability of air and by the mounting arrangement in the tunnel. As a result the aspect ratio of the wing was less than one. With a larger aspect ratio wing which spanned the tunnel the lift, drag, and aerodynamic moment could have been estimated from the experimental data in Ref. 8, 9, and 10.

With a different jet-flap design the wing could also have had a shorter chord length. This would reduce the weight per unit span, improve the aspect ratio and reduce the moment of inertia. A wing with this improved geometry would then be easier to excite with the gust generator.

B. RECOMMENDATIONS

1. Control System

The vane and jet sensor arrangement could be improved by fixing the vane to the wing and by building a rotating fixture for the jet sensors. The sensors would then be aligned to the vane thus setting the angle of attack.

For a truly optimal control system the switching locus of the control jets should be computed by the control system rather than set by the operator. This would eliminate the adjustment problem with the spacing of sensors J2. To do this requires the design of a timing circuit if the system is to remain purely digital. If a satisfactory vortex rate sensor were available it could be used to input velocity data to a hybrid computer network of proportional and digital fluidic devices.

In order to take advantage of the reliability of fluidic devices, it was intended throughout this project to avoid electrical or electronic components. By allowing their use, a designer would have more flexibility. A hybrid system with electronic sensors and fluidic logic might provide the optimum combination of sensitivity, response and reliability. In this project as in Rose and Smith's [4] the system performance was degraded by the sensors. At present the interface devices to convert electronic signals to fluidic signals are not available. Miniaturized solenoid valves would have to be fabricated for such an application.

2. Wing Design

The aspect ratio of the wing should be increased to at least two. Additional air compressor capacity must be acquired to supply a full-span jet-flap.

To increase the jet deflection angle, it is recommended that the gap between the control jets and the power jet be closed. This could be accomplished by filling the space between the tubes with DEVCON and fairing the filler material to the contour of the tubes. This would provide a continuous solid boundary to which the jet could attach.

3. Wind Tunnel and Model Mounting

When the wind tunnel is operating the small pressure difference across the large tunnel doors creates a considerable net force on the doors. Deflections of nearly one-half inch have been observed at the center of the doors. The plexiglas should be reinforced or preferably the doors should be replaced by smaller ones.

The present mounting stands must be completely disassembled in order to open the wind tunnel door. With this arrangement it takes at least an hour to install the wing. Most of this time is spent in aligning the mounting pedestals. It is suggested that a concrete block, with steel channels imbedded in the top, be built up to the base of the test section. Any type of mounting fixture could then be bolted to the steel and arranged for easy assembly and disassembly.

C. SYSTEM SCALE

The control system was designed and built for a wing model to be tested in a wind tunnel. The question arises, "Can this system be adapted to an actual aircraft?" The answer is necessarily conditional; a yes answer can only be given after the fact. The requirements which must be satisfied include:

a) a fixed frame of reference (stable element),

b) ducting for air from engine to flap,

c) an interface device capable of handling the air volume necessary for an effective flap (not a valve),

d) a supply of clean dry air for the fluidics.

For complete gust alleviation the system must also maintain constant lift in the gust field in order to eliminate purely vertical accelerations. This means there must be jet-flaps on the wings and tail to control lift and pitch simultaneously. The jet-flap may also be used as a lift augmentation device, particularly in V/STOL applications. A manual control of jet deflection would be necessary for this purpose.

Development of jet-flapped V/STOL aircraft is just now getting underway. Fluidic devices may find applications in the control systems for these aircraft.

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A fluidic control system was designed, built, and tested for a jet-flap airfoil. The system was required to alleviate low frequency pitching moments caused by gusts in the airstream. An optimal, maximum effort control strategy was used.

The control system used digital fluidic devices exclusively. Details of the control system design procedure are presented. The construction of the jet-flap airfoil and a companion gust generator are also discussed.

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20. (cont'd)

Results of wind tunnel testing are tabulated and critiqued. The control system was effective in alleviating gusts of frequency less than two Hertz. System improvements are required for operation at higher frequencies.

Melanephy

A fluidic control system for a jet-flap airfoil.